Mechanistic Studies on the Alkylation of Pentane-2,4-dione through its Co(II) Complex

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Abstract. A mechanistic study on the alkylation of pentane-2,4-dione through its Co(II) complex in concentrated chloroform solutions indicates the operation of a "non carbon radical" chain mechanism based in the ability of cobalt to undergo redox processes between the Co(III) and Co(I) states, including oxidative addition and reductive elimination steps. This process is initiated by inner sphere electron transfer induced by Co(II).

INTRODUCTION

The use of β-diketones in the form of their nickel(II),[1] cobalt(III),[2] zinc(II),[2] and mainly copper(II)[3] and cobalt(II)[4] complexes has broadened the scope of their C-alkylation reactions. Thus, Co(II) complexes of β-dicarbonyl compounds have been alkylated (Scheme 1) with easily dehydrohalogenable alkyl halides,[4a] non active halides such as 1-bromoadamantane[4b] and 2-bromoadamantane,[4c] and other special alkyl halides such as 9-bromofluorene.[4d] These procedures have been particularly useful in the regioselective alkylation of methyl 3,5-dioxohexanoate, a β,δ-diketoester considered as a polyketide model.[5]

Our first studies on the alkylation of cobalt(II) complexes of β-dicarbonyl compounds were carried out in relatively dilute CHCl₃ solutions.[2,4a] In those conditions the reaction showed the features of a slow carbocationic process.[2] However, by carrying out the reactions in concentrated solutions, a faster and more efficient novel process was elicited. Qualitative mechanistic studies[6] led us to the preliminary conclusions that alkylcobalt(III) species were involved and that we were dealing with a chain (perhaps radical) process based in the cobalt ability of undergoing redox processes between the Co(I) and the Co(III) oxidation states.

Several examples of the use of Co(II) species, in some cases catalytically,[7,8] to achieve a variety of transformations have been reported in the literature. Thus, oxiranes can be opened to β-hydroxysulfides in the presence of CoCl₂ or Co₂(CO)₈.[9] Other examples are the acylative cleavage of ethers,[10] the condensation of acetoacetate with vinyl ethers,[11] etc. Even though no mechanistic studies have been performed on those reactions, the authors postulate in several cases alkylcobalt(III) species as intermediates.[12]

Alkylcobalt(III) complexes produce, under thermolysis or photolysis, alkyl radicals. This is a key step in the action mechanism of vitamin B₁₂.[13] This general ability of alkyl cobalt(III) complexes has been preparatively used mainly to achieve radical cyclizations.[14]

Alkyl cobalt(III) complexes derived from Schiff bases are relatively stable, they can be isolated,[15] and their reactions have been mechanistically studied by standard methods.[16] However, alkyl cobalt(III)

complexes with oxygen ligands seem to be much more unstable,[17] and as far as we know no monoalkylcobalt(III) complexes of β-dicarbonyl compounds have been reported.

Considering the importance of the reactions where cobalt is involved, and the lack of mechanistic information about the reactions of their complexes with ligands other than Schiff bases, we decided to carry out a mechanistic study on the reactions of (acac)$_2$Co [(bis(pentane-2,4-dionate)cobalt(II)] with alkylating agents (Scheme 1), using high concentration conditions, where the chain mechanism[6] was operative.
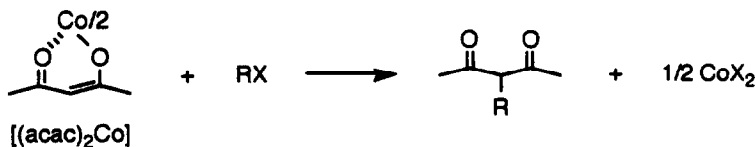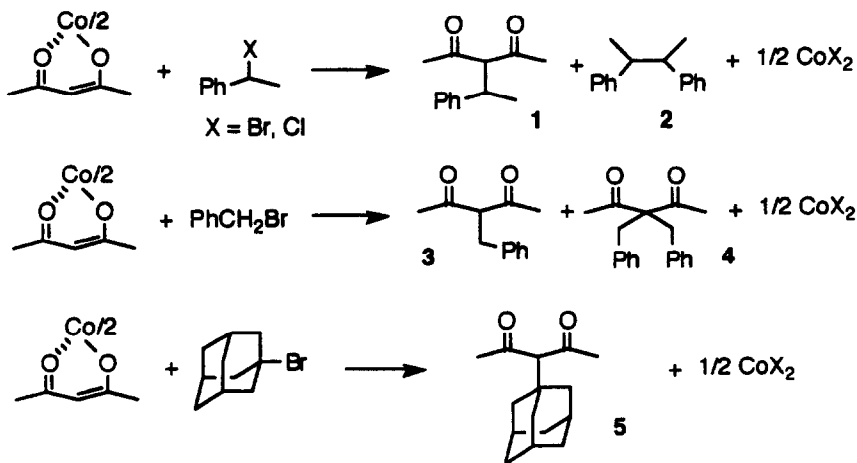

Scheme 1

RESULTS

Preparative Studies and Product Analyses.

The reaction described in Scheme 1 was carried out with several 1-phenylethyl alkylating agents under high concentration conditions. Thus, the reaction between 1-bromo-1-phenylethane and (acac)$_2$Co with solvent (CHCl$_3$) evaporation, led to the diketone monoalkylation product, **1** (65% yield), in only 10 min. The corresponding reaction with 1-chloro-1-phenylethane result to be slower but the monoalkylation product could be obtained in fair yield (70%) in 45 min. The corresponding reactions using OH, OCH$_3$, OCOCH$_3$ as leaving groups where unsuccessful leading to the recovery of the starting materials. When the reaction between (acac)$_2$Co and 1-bromo-1-phenylethane was carried out in a sealed vessel (45 min., 80C, alkylating agent concentration = 2.92M), in addition to the monoalkylation product, **1**, a 28% yield of the dimeric isomers (*meso* and *d,l*) 2,3-diphenylbutane, **2**, was isolated (Scheme 2).

Scheme 2

Similar reactions were carried out with benzyl bromide and 1-bromoadamantane as alkylating agents. In addition to the C-monoalkylation products, **3** and **5**, the dialkylation product 3,3-dibenzylpentane-2,4-dione, **4**, was also obtained in the first case.

Kinetic Studies

Rigorous kinetic studies in reactions where transition metal complexes are involved, are not common. (Acac)$_2$Co is a tetramer in the solid state,[18] and no information exists about their structure in solution, and how this can vary with the concentration. Therefore, we decided to monitor the products production (**1** and **2**) with time in several reactions, the starting concentration, and the presence of some additives introduced in the reaction mixture, being the variable factors. The evolution of the reaction of (acac)$_2$Co with 1-bromo-1-phenylethane (Scheme 2, X=Br) with time, at different starting material concentrations are shown in Tables 1, 2, and 3 . The same is indicated in Tables 4 and 5 for 1-chloro-1-phenylethane. In this case the reaction is slower, therefore we carried out parallel experiments at a higher temperature (100°C) and the results are indicated in Table 6.

Once the concentration effect had been established, reactions were performed in the presence of different additives. Thus, when a 0.1 eq. CoCl$_2$(PPh$_3$)$_2$ (soluble in chloroform) was added to the reaction of 1-bromo-1-phenylethane (0.73M) with (acac)$_2$Co at 80°C, a 56% yield of alkylation product **1** was obtained after 30 minutes. The corresponding blank reaction (in the absence of the additive) gave only a 5% yield, thus demonstrating the reaction was catalyzed by Co(II) species. On the other hand, when 0.25 eq. of the radical scavenger galvinoxyl was added to the same blank reaction, the reaction showed the evolution with time indicated in the Table 7.

The reactions of (acac)$_2$Co with other alkylating agents as benzyl bromide and 1-bromoadamantane have been also studied, and their evolution with time is described in Tables 8 and 9.

Table 1. Evolution of the Reaction between (acac)$_2$Co and 1-Bromo-1-phenylethane at 80°C and [PhCH(CH$_3$)Br] = 2.92M.[a]

Time (min.)	17	30	35	45	75	120	180
Product **1** (%)	4	6	46	46	61	73	80
Product **2** (%)	6	4	22	16	28	b	b

a) Molar ratio RX / (acac)$_2$Co = 2. b) Not monitored

Table 2. Evolution of the Reaction between (acac)$_2$Co and 1-Bromo-1-phenylethane at 80°C and [PhCH(CH$_3$)Br] = 0.73M.[a]

Time (min.)	30	50	75	85	90	135	360
Product **1** (%)	5	5	12	33	41	58	72
Product **2** (%)	0	0	3	8	16	31	b

a) Molar ratio RX / (acac)$_2$Co = 2. b) Not monitored

Table 3. Evolution of the Reaction between (acac)$_2$Co and 1-Bromo-1-phenylethane at 80°C and [PhCH(CH$_3$)Br] = 0.18M.[a]

Time (min.)	60	90	165	300
Product **1** (%)	1	8	8	9
Product **2** (%)	0	0	0	0

a) Molar ratio RX / (acac)$_2$Co = 2

Table 4.   Evolution of the Reaction between (acac)$_2$Co and 1-Chloro-1-phenylethane at 80°C and [PhCH(CH$_3$)Cl] = 2.92M.[a]

Time (min.)	180	225	240	285	330	375
Product 1 (%)	0	0	0	24	50	58
Product 2 (%)	0	0	0	7	15	16

a) Molar ratio RX / (acac)$_2$Co = 2

Table 5.   Evolution of the Reaction between (acac)$_2$Co and 1-Chloro-1-phenylethane at 80°C and [PhCH(CH$_3$)Cl] = 0.73M.[a]

Time (min.)	330	405	420
Product 1 (%)	0	2	4
Product 2 (%)	0	0	0

a) Molar ratio RX / (acac)$_2$Co = 2

Table 6.   Evolution of the Reaction between (acac)$_2$Co and 1-Chloro-1-phenylethane at 100°C and Different Reagents Concentrations.[a]

Time (min.)	23	30	45	90	120	150	210	270
Prod. 1 (%) [PhCH(CH$_3$)Cl] = 2.92M	7	58	70	b	b	b	b	b
Prod. 1 (%) [PhCH(CH$_3$)Cl] = 0.73M	0	0	0	9	46	66	b	b
Prod. 1 (%) [PhCH(CH$_3$)Cl] = 0.18M	0	0	0	0	0	6	30	29

a) Molar ratio RX / (acac)$_2$Co = 2   b) Not monitored

Table 7.   Evolution of the Reaction between (acac)$_2$Co and 1-Bromo-1-phenylethane at 80°C and [PhCH(CH3)Br] = 0.73M in the Presence of 0.25 eq. of Galvinoxyl.[a]

Time (min.)	120	165	210
Product 1 (%)	<5	46	48

a) Molar ratio RX / (acac)$_2$Co = 2

Table 8.   Evolution of the Reaction between (acac)$_2$Co and Benzyl Bromide at 80°C and [PhCH$_2$Br] = 2.92M.[a]

Time (min.)	75	90	105	120	165	450
3-Benzylpentane-2,4-dione, 3 (%)	21	21	39	51	57	57
3,3-Dibenzylpentane-2,4-dione, 4 (%)	5	6	6	31	26	33

a) Molar ratio RX / (acac)$_2$Co = 2

Table 9.   Evolution of the Reaction between (acac)$_2$Co and 1-Bromoadamantane at 120°C and [1-bromoadamantane] = 2.92M.[a]

Time (min.)	60	205	225	240	285	310	325	345
3-(1-Adamantyl)pentane-2,4-dione, 5 (%)	0	0	51	84	84	84	95	95

a) Molar ratio RX / (acac)$_2$Co = 2

Radical Clocks

The use of cyclizable probes also known as "radical clocks" has been one of the mechanistic diagnosis methods more commonly used in the study of reactions suspicious of including free radicals as intermediates.[19] Typical reagents of this kind are 5-hexenyl derivatives. Some precautions have to be taken when using such derivatives since the indiscriminate use of bromides and iodides can give misleading evidence due to their ability of transfering the halogen atom to any radical source (even present in very small amount), eliciting a chain reaction. Only the chlorides are reagents safe enough for these kind of studies.[20] Therefore, we decided to use 1-chloro-1-phenyl-5-hexene, **6**, as alkylating agent in reactions with (acac)$_2$Co. The results are described in Scheme 3. Thus, the reaction of (acac)$_2$Co with 1-chloro-1-phenyl-5-hexene, **6**, at 120C and high concentration conditions ([**6**] = 4.7M) led to the the dehydrohalogenation product 1-phenyl-1,5-hexadiene (**7**, 46% yield), the cyclization product 1-chloro-3-phenylcyclohexane (**8**, 42% yield), and the alkylation product 3-(1-phenyl-5-hexen-1-yl)pentane-2,4-dione, (**9**, 10% yield). **No cyclized alkylation products could be detected.**
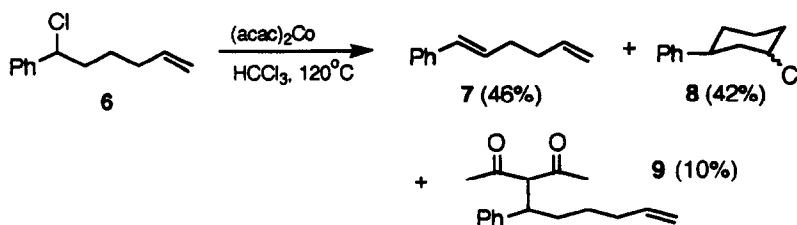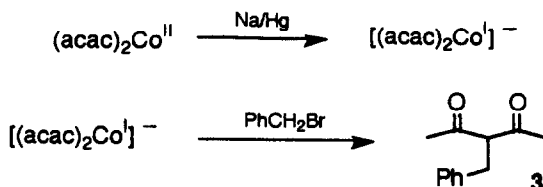

Scheme 3

There are some precedents of product **6** cyclization, and at first sight the exclusive appearance of the six membered cyclized product (**8**) (no five-membered ring product derived from the cyclopenthylmethyl radical could be detected) is surprising. However, this result agrees with those of Walling *et al.*[21a] that have studied the interconversion among the 1-phenyl-5-hexenyl, 2-phenylcyclopentylmethyl, and 3-phenylcyclohexyl radicals observing the major products were derived from the 3-phenylcyclohexyl radical. When the phenyl ring is not present in position 1, the products derived from the cyclopentylmethyl radicals predominate.[21b] However, M. Julia *et al.*[22] report (without experimental details) the cyclization of **6** to **8** in the presence of CuCl, but the major product result to be 2-phenylcyclopenthylmethyl cloride.

Reactions Using Co(I) Species.

In order to support the initial hypothesis (see the discussion part) that Co(I) and Co(III) species were involved in our reactions, we studied the possibility of eliciting the process starting from Co(I) complexes. As a first approach, the well established methodology[23] for preparing alkylcobalt(III) complexes with imine and oxime ligands, starting from the corresponding anionic cobalt(I) complex, was followed. Thus, (acac)$_2$Co was reduced with sodium amalgam in anhydrous THF [molar ratio (acac)$_2$Co/Na = 1] and the resulting [(acac)$_2$Co]⁻ was allowed to react with benzyl bromide. The process afforded 64% yield (based on sodium as limiting reagent) of 3-benzylpentane-2,4-dione, **3**, (scheme 4). The use of a larger amount of sodium amalgam resulted in lower yields and the formation of a metallic cobalt(0) mirror. We were unable to isolate or even detect the alkylcobalt(III) intermediate even when the process was carried out in the presence of pyridine, thus confirming the low stability of such complexes in the absence of imine or oxime ligands. It is significant for the following discussion the fact that the process is not catalytic in sodium, and therefore, only one of the (acac) ligands is consumed. On the other hand, the nature of the leaving group is important since a similar reaction (relatively mild conditions) starting from the corresponding acetate failed.
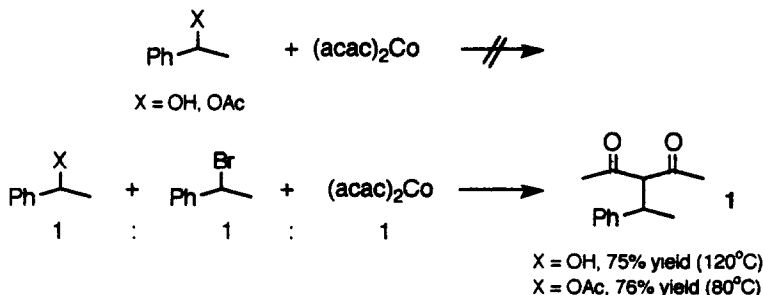
Scheme 4

The possibility of initiating the reaction from a neutral Co(I) complex was tested. The reaction between pentane-2,4-dione and 1-bromo-1-phenylethane in the presence of $CoCl(PPh_3)_2$, under inert atmosfere [*in situ* formation of a "(acac)Co" species was expected], afforded the monoalkylation product, **1**. The relative efficiences of $CoCl(PPh_3)_3$ and $CoCl_2(PPh_3)_3$ as catalysts[8] were compared resulting to be similar.

Reactions Using Mixtures of Alkylating Agents with Different Leaving Groups.

The experiments described so far show a dependence of the reaction result with the leaving group. At this point we thought that perhaps if a halide was able to initiate the process, the reaction could be mantained with a different type of alkylating agent, for instance an alcohol or an acetate. This proved to be true, with the only limitation of the rather high proportion of halide needed for the reaction to succeed. Thus, 1-phenylethanol is inert *versus* (acac)$_2$Co, in the normal conditions used in this work, even in the presence of catalytic amounts of $CoCl_2(PPh_3)_3$ (this demonstrates that no OH/halide exchange occurs under the reaction conditions), but when a mixture 1/1/1 molar of 1-phenylethanol, 1-bromophenylethane, and (acac)$_2$Co in chloroform was heated at 120°C, with solvent evaporation, 75% yield of the alkylation product, **1**, was obtained (scheme 5). This result indicates that the alcohol has been at least partially consumed.

Scheme 5

The same result was obtained when acetates were used instead of alcohols (scheme 5). In this case a lower temperature was enough.

These results indicate that the halide initiates the process, but the reaction (probably a cycle) can proceed, at least partially, with alkylating agents having other leaving groups as hydroxy or acetoxy.

DISCUSSION

The analysis of the reported results indicates we are in the presence of a rather complex process. First of all, we can identify two different mechanisms that as a common and important feature show the total absence of O-alkylation products:

A)   "Slow polar process" in refluxing chloroform diluted solution.[2]

B) Fast process, that shows an induction period and that can be elicited placing the reaction mixture in concentrated solution.
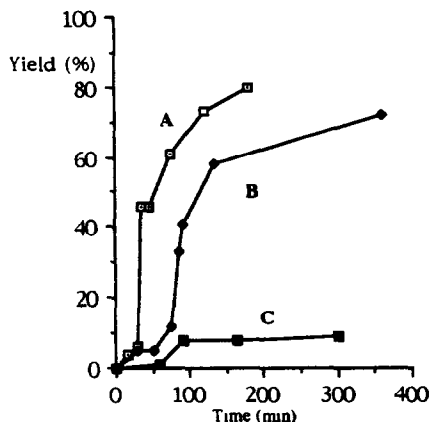

Fig. 1 Evolution of the reaction between $(acac)_2Co$ and 1-bromo-1-phenylethane at 80°C (product 1 is monitorized) at different $[PhCH(CH_3)Br]$ concentrations: (A) = 2.92M; (B) = 0.73M; (C) = 0.18M (data taken from tables 1, 2, and 3).
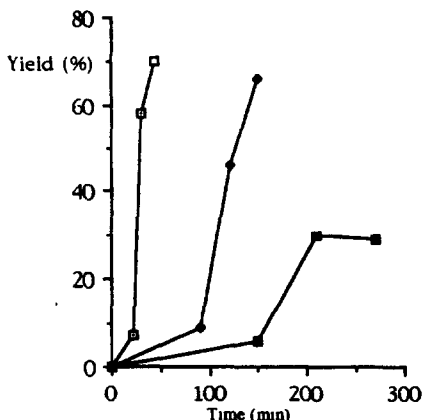

Fig. 2 Evolution of the reaction between $(acac)_2Co$ and 1-chloro-1-phenylethane at 100°C (of product 1 is monitorized) at different $[PhCH(CH_3)Cl]$ concentrations: (A) = 2.92M; (B) = 0.73M; (C) = 0.18M (data taken from table 6).
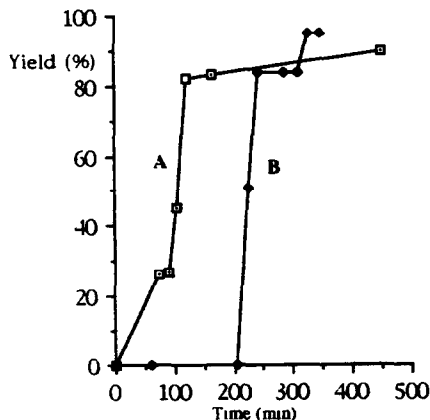

Fig. 3 Evolution of the reaction between $(acac)_2Co$ and: (A), benzyl bromide at 80°C [RX] = 2.92M (data taken from table 8); (B), 1-bromoadamantane at 120°C [RX] = 2.92M (data from table 9). Total formation of alkylation products is monitorized,
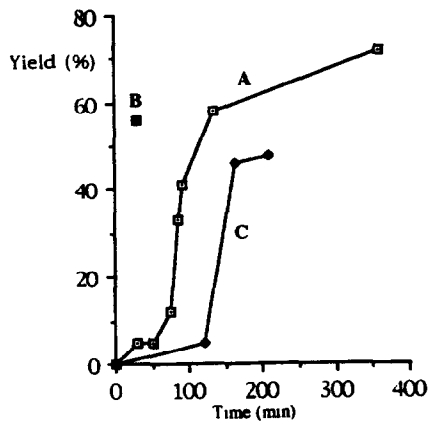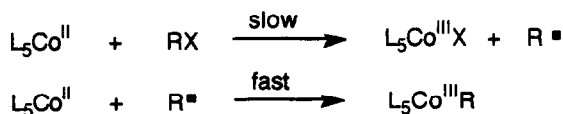

Fig.4 Evolution of the reaction between $(acac)_2Co$ and 1-bromo-1-phenylethane at 80°C (product 1 is monitorized) at $[PhCH(CH_3)Cl] = 0.73M$ (A), in the presence of $CoCl_2(PPh_3)_3$, (B), and galvinoxyl, (C) (data taken from table 2 and 7).

Our studies have concentrated on process "B". The first important feature of this process is its rate. The reaction once started is almost instantaneous (at least up to 50% yield) suggesting we are in the presence of a chain reaction. As a first hypothesis a $S_{RN}1$ type mechanism was considered. This hypothesis was rejected on the basis of the reactivity of the different leaving groups used, and the behaviour of the reaction in the presence of the radical scavenger galvinoxyl, that suggested the presence of free radicals only in the initiation steps. Indeed, from Fig. 4 it is evident that galvinoxyl increases the induction period but once the reaction is triggered, its kinetics is the same that in the absence of galvinoxyl. The results obtained with cyclizable probes ("radical clocks") also indicated the absence of free radicals in the hypothetical propagation cycle.
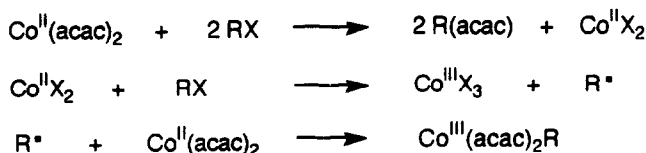
The Initiation Steps

In figures 1-4, the kinetic behavior of the reactions of $(acac)_2Co$ with different alkylating agents at different concentrations are described. The reactions show in all the cases an induction period that is reduced at higher concentration. Once the reactions start, they are almost instantaneous at least up to 50% yield (figure 1). In figure 4 the effects of additives is shown for a model case . These results indicate the reaction is autocatalyzed (the induction period is reduced in the presence of $CoCl_2$), and that free radicals are only present in the initiation steps (galvinoxyl increases the induction period but the process once elicited is almost instantaneous). The isolation of radical dimers (product **2**, scheme 2) support the conclusion that alkyl free radicals are present at least in the initiation step.

Our experiments indicate the reaction is very sensitive to the leaving group, I^{4c} > Br > Cl > triphenylpyridine.[24] acetoxy. hydroxy. However. it is possible to succeed in using alkylating agents with hydroxy or acetoxy leaving groups if the reaction is initiated with an alkyl halide. We think that in the initiation steps a coordination must exist between the metal atom and the leaving group, leading to a inner sphere electron transfer (electron transfer with atom transfer), and that this step is only possible with halides as a leaving groups. The same results indicate that this step is not present in the propagation steps.

$$L_5Co^{II} \ + \ RX \ \xrightarrow{slow} \ L_5Co^{III}X \ + \ R\bullet$$

$$L_5Co^{II} \ + \ R\bullet \ \xrightarrow{fast} \ L_5Co^{III}R$$

Scheme 6

All the data referred to the initiation steps can be accomodated to the Halpern general scheme for the interaction of a Co(II) species with an alkyl halide (scheme 6).[25] In our case it will include a slow first step (perhaps responsible of the induction period) that would produce an active Co(II) species [the $(acac)_2Co$ in the solid state is a coordinatively saturated tetramer]. This active species could even be the CoX_2 produced in small amount in the "slow polar mechanism A". These initiation steps (scheme 7) would produce an alkylcobalt(III) complex intermediate that would start the chain (propagation steps).

$$Co^{II}(acac)_2 \ + \ 2\,RX \ \longrightarrow \ 2\,R(acac) \ + \ Co^{II}X_2$$

$$Co^{II}X_2 \ + \ RX \ \longrightarrow \ Co^{III}X_3 \ + \ R\bullet$$

$$R\bullet \ + \ Co^{II}(acac)_2 \ \longrightarrow \ Co^{III}(acac)_2R$$
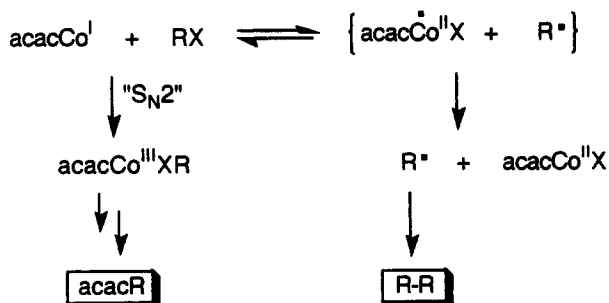
Scheme 7

The Propagation Steps

The crucial experiments to put forward a reasonable hypothesis for the propagation steps are the commented behaviour of the reaction in the presence of galvinoxyl (fig. 4) and the absence of cyclized alkylation products in the experiment with cyclizable probes. As previously stated, those experiments suggest the absence of alkyl free radicals in the propagation cycle. Therefore, our hypothesis is based in the ability of cobalt to undergo redox processes between the Co(I) and Co(III) states, including oxidative addition and reductive elimination steps (scheme 8). Similar catalytic cycles have been proposed in the literature for several processes where cobalt species are involved.[26]

$$(acac)_2Co^{III}R \longrightarrow acacCo^I + \boxed{acacR}$$

$$acacCo^I + RX \longrightarrow acacCo^{III}XR$$
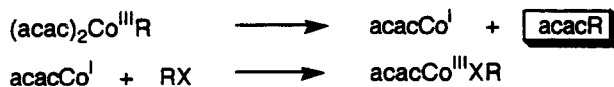
Scheme 8

Our results confirm the operation of Co(I) species as intermediates. The reactions can be carried out using either anionic or neutral Co(I) complexes (scheme 4). In those experiments, the influence of the leaving group is evident (Br > AcO in the reactions carried out with anionic Co(I) complex). However the reactions of the Co(II) complex, initiated with an alkyl halide can consume alcohols or acetates. Therefore, even though there is an effect of the leaving group nature in the propagation steps, this effect seems to be smaller than the one observed in the initiation steps. This leaving group effect (and the absence of free radicals in the propagation cycle) could be explained by assuming the oxidative addition step follows an S_N2 mechanism. There are a number of studies in the literature on the reactions of d^8 complexes (Rh(I)[27] and Co(I)[28]) with alkylating agents. For complexes with good nucleophilic properties as the Co(I) ones, the S_N2 mechanism is the more commonly accepted mechanism. Of course, this would not be the case when 1-bromoadamantane is used as alkylating agent (Table 9, Fig. 3). No mechanistic studies have been carried out in this case yet, but it is possible that a different oxidative addition mechanism (perhaps through outer sphere electron transfer) could be operating in this case.
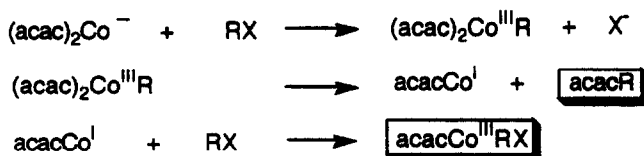
$$acacCo^I + RX \rightleftharpoons \left\{ acac\overset{\bullet}{Co}^{II}X + R^\bullet \right\}$$

$$\downarrow "S_N2" \qquad\qquad\qquad \downarrow$$

$$acacCo^{III}XR \qquad\qquad R^\bullet + acacCo^{II}X$$

$$\downarrow \qquad\qquad\qquad\qquad \downarrow$$

$$\boxed{acacR} \qquad\qquad\qquad \boxed{R\text{-}R}$$

Scheme 9

There are a couple of confusing results that merit some extra discussion. First, the proportion of radical dimer observed in some cases (28%, scheme 2), exceedes the expected, considering it comes from the initiation steps. This result seems to be contradictory with these found in the presence of galvinoxyl and when cyclizable probes are used. The explanation can come from the second confusing result. In the experiment carried out with the cyclizable probe 1-chloro-1-phenyl-5-hexene, **6**, no cyclized alkylation product could be detected, but cyclization of the starting halide was observed (scheme 3). It seems we are in the presence of two competing processes in the oxidative addition step, first, the already commented "S_N2" mechanism that

would lead to the alkylation products via reductive elimination, and secondly, a "inner sphere electron transfer - caged radical pair"[29] mechanism (scheme 9). This would produce reversibly a radical pair outside the pathway leading to the alkylation products, that would justify the appearance of cyclized starting material (return from the radical pair), and radical dimer (radical collapse outside the cage). The cyclized starting material, not being neither benzylic nor allylic, nor tertiary, is not active in front of Co(I) and accumulates.

Before to put forward our final proposal, lets consider two, apparently, not related results. First, in the experiment carried out starting from the anionic complex [(acac)$_2$Co]$^-$, only one (acac) unit was consumed. In this case, and following our model, all the cobalt ends as (acac)Co^{III}RX (scheme 10). Therefore, this complex seems to be relatively inert to the reductive elimination. This means to us, that for getting an efficient reductive elimination , two (acac) units must be present in the complex. This could explain the fact that, in some cases (Fig.1), there is an important difference in rate between the process that consumes the first (acac) unit (50% yield) and the process that consumes the second. If we consider (acac)Co^{III}RX stable to the reductive elimination, the ligand exchange step (acac / X), necessary to keep the cycle alive, must happen after only one (acac) unit has been consumed.

$$(acac)_2Co^- \ + \ RX \ \longrightarrow \ (acac)_2Co^{III}R \ + \ X^-$$

$$(acac)_2Co^{III}R \ \longrightarrow \ acacCo^I \ + \ \boxed{acacR}$$

$$acacCo^I \ + \ RX \ \longrightarrow \ \boxed{acacCo^{III}RX}$$

Scheme 10

Therefore we end up (scheme 11) with two very similar interconnected cycles with their respective rates governed by the corresponding ligand exchange step, faster going from (acac)$_2$Co to (acac)CoX than from this to CoX$_2$.
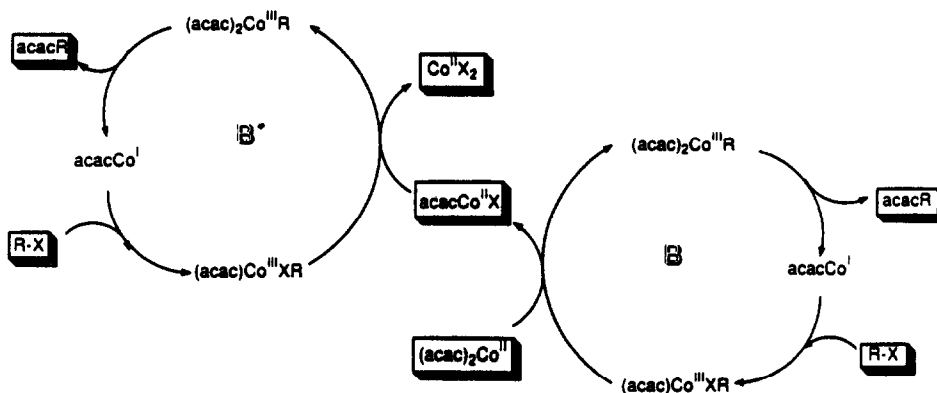
Scheme 11

EXPERIMENTAL

All melting points are uncorrected. ^{1}H NMR were recorded at 80 or 400 MHz and the ^{13}C NMR at 20 or 100 MHz. The GC analyses were performed using a HP-Crosslinked Dimethylsilicone Gum 12m x 0.2mm x 0.33m film thickness capillary column. 1-Bromo-1-phenylethane[30] was prepared by benzylic bromination of ethyl benzene with NBS. 1-Chloro-1-phenylethane was prepared through the reaction of thionyl chloride with 1-phenylethanol. 1-Phenylethyl acetate[31] was also prepared from 1-phenylethanol. 1-Chloro-1-phenyl-5-hexene[32], 6, was prepared from 1-phenyl-5-hexen-1-ol by reaction of this with thionyl chloride in pyridine. 1-Phenyl-5-hexen-1-ol[33] was prepared by reaction of pent-4-en-1-ylmagnesium bromide with benzaldehyde. Cobalt(II)bistriphenylphosphine chloride[34] and Cobalt(I)tristriphenylphosphine chloride[35] were prepared following the literature methods.

Preparative Reactions in Concentrated Solution.

Reaction of (acac)₂Co with 1-Bromo-1-phenylethane. 1-Bromo-1-phenylethane (0.270 g, 1.46 mmol), 0.188 g of (acac)₂Co (0.73 mmol) and 0.5 ml of chloroform ([PhCH(CH3)Br] = 2.92M) were introduced in a 25 mL sealed reactor. The mixture was heated at 80°C for 1 h. Then, the formed solid was filtered and washed several times with chloroform. The organic solution was evaporated, giving 0.119 g of residue that was chromatographed through silica gel using hexane/CH₂Cl₂ as eluent . The following products were isolated: 2,3-Diphenylbutane[36], 2, (0.032 g, 21 % yield) as a mixture of the two diastereoisomers, *meso* and *d,l* (b.p. 76°C, 0.002 Torr): ^{1}H RMN (CDCl₃) 1.33 (d, J = 6Hz, 3H), 1.43 (d, J = 6Hz, 3H), 4.2 (q, J = 6 Hz, 1H), 4,47 (q, J = 6 Hz, 1H), 7.25 (broad, 10H). 3-(1-Phenylethyl)pentane-2,4-dione, 1, (0.162 g, 54% yield) mp 48-49°C (lit[37] 49C): IR (CHCl₃) 3050, 3000, 1700, 1600, 1500, 1460 cm⁻¹; ^{1}H NMR (CDCl₃) 1.2 (d, J = 6.4Hz, 3H), 1.9 (s, 3H); 2.3 (s, 3H); 3.37-3.82 (dq, J = 11.5Hz, J = 6.4Hz, 1H); 4.06 (d, J = 11.5Hz, 1H), 7.25 (5H); Ms, m/e (relative intensity) 204 (M⁺, 1), 186 (23), 162 (15), 161 (100), 147 (35), 143 (35), 129 (20), 105 (25), 43 (47).

Reaction of (acac)₂Co with benzyl bromide. Benzyl bromide (0.250 g, 1.46 mmol), (acac)₂Co (0.188 g, 0.73 mmol) and 0.5 mL of chloroform were introduced in a 25 mL sealed reactor. The mixture was heated at 120°C for 1 h. The reaction was worked up as previously reported[38] for the diluted reaction, yielding 0.142 g (51% yield) of 3-benzylpentane-2,4-dione, 3, bp 65-75°C, 0.2 Torr (lit[39] 135-136°C, 7 Torr) and 0.059 g (15% yield) of 3,3-dibenzylpentane-2,4-dione, 4, mp 112-114°C (lit[40] 113°C).

Reaction of (acac)₂Co with 1-Bromoadamantane. 1-Bromoadamantane (0.308 g, 1.43 mmol), (acac)₂Co (0.188 g, 0.73 mmol), CoCl₂ (0.210 g, 1.46 mmol), and 2 mL of chloroform ([RX] = 0.73M) were introduced in a 25 mL sealed reactor. The mixture was heated at 80°C for 17 h. Next, the reaction was worked up as previously reported[4b] for the diluted reaction, yielding 0.225 g (76% yield) of 3-(1-adamantyl)pentane-2,4-dione, 5, mp 54-55°C (lit[4b] 54°C).

Reaction of (acac)₂Co with 1-Chloro-1-phenyl-5-hexene, 6. 1-Chloro-1-phenyl-5-hexene, 6 (0.912 g, 4.7 mmol), (acac)₂Co (0.988 g, 3.84 mmol), and 1 mL of chloroform were introduced ([6] = 4.7M) in a 25 mL sealed reactor. The mixture was heated at 100°C for 17 h. It was partitioned between chloroform and 1N HCl. The residue obtained after evaporation of the organic layer was chromatographed through silica gel using hexane/CH₂Cl₂ as eluent. The following products were isolated and characterized: 1-Phenyl-1,5-hexadiene[41] (7, 0.345 g, 46% yield): IR (film) 3083, 3028, 2935, 1602, 1494, 754, 699 cm⁻¹; ^{1}H NMR (CDCl₃) 1.5-2,5 (m, 4H), 5.0 (d, J = 9.7Hz, 1H), 5.06 (d, J = 17.0Hz, 1H), 5.6-6.6 (m, 3H), 7.23 (5H); MS m/e (relative intensity) 158 (M⁺,9), 117(100), 115(70), 91(27), 77(7), 41(12), 39(21). 1-Chloro-3-phenylcyclohexane, 8, (0.383 g, 42% yield) bp 80°C 0.15 Torr, as diastereomeric mixture: IR (film) 3029, 2937, 1494, 1448, 1270, 756, 699; ^{1}H NMR (CDCl₃) *cis* diastereoisomer (equatorial-equatorial, 59%) 1.19-2.48 (m, 8H), 2.60 (tt, J_{ax-ax} = 11.2Hz, J_{ax-eq} = 3.7Hz, 1H), 3.97 (tt, J_{ax-ax} = 11.2 Hz, J_{ax-eq} = 3.7Hz,

1H), 7.00-7.44 (m, 5H); *trans* diastereoisomer ax-eq (41%) 1.19-2.48 (m, 8H), 3.14 (tt, $J_{ax-ax} = 11.2Hz$, $J_{ax-eq} = 3.70Hz$, 1H), 4.63 (m, 1H), 7.00-7.44 (m, 5H); ^{13}C NMR (CDCl₃) *cis* diastereoisomer 20.53, 37.48, 41.37, 59.31; *trans* diastereoisomer 26.14, 36.98, 44.38, 44.72, 59.87; the other signals have not been assigned separately to the individual diastereoisomers 32.76, 33.36, 33.57, 126.11, 126.33, 126.63, 126.90, 128.47, 128.40, 145.15, 145.41; MS m/e (relative intensity) 196 (M⁺+2, 7), 194 (M⁺, 17), 158 (35), 143 (13), 129 (23), 117 (57), 115(33) 104 (33), 91 (100), 78 (33), 77 (28), 51(51), 41(43); calculated for C₁₂H₁₅Cl: C, 74.01; H, 7.78; Cl, 18.20; found: C, 73.78; H, 7.91; Cl, 18,72. 3-(1-Phenyl-5-hexen-1-yl)pentane-2,4-dione, **9**, bp 110-125°C 0.05 Torr: IR (film) 3085, 3029, 2932, 1725, 1698, 1640, 1494, 1454, 1358, 1217, 1186, 1153, 752, 702 cm⁻¹; ¹H RMN (CDCl₃) 1.06-1.64 (m, 4H), 1.78 (s, 3H), 1.79-2.18 (m, 2H), 2.24 (s, 3H) 3.44 (m, 1H), 4.09 (d, J = 10.9Hz, 1H), 4.73-5.05 (m, 2H), 5.69 (m, 1H), 7.03-7.39 (m, 5H); ^{13}C NMR (CDCl₃) 26.05, 29.7, 30.85, 33.22, 33.75, 44.60, 76.33, 114.69, 127.01, 128.11, 128.66, 138.21, 140.60, 203.30, 214.39; MS m/e (relative intensity) 215 (M⁺-43, 9), 147 (15), 129 (11), 117 (14), 104 (7), 91 (26), 43 (100), 41 (11); calculated for C₁₇H₂₂O₂: C, 79.03; H, 8.58; found: C, 79.13; H, 8.68.

Reaction of [(acac)₂Co]⁻ with benzyl bromide. Sodium amalgam was prepared from 0.140 g of sodium and 7.3 mL of Hg. 200 mL of THF and the freshly prepared sodium amalgam were introduced in a 250 mL round bottom flask. Next, and under inert atmosphere, 1.6 g (6 mmol) of (acac)₂Co were also introduced, and the mixture left at room temperature overnight. Then, the mixture was cooled to 0°C and the THF solution transferred, also under inert atmosphere to another 250 mL round bottom flask where previously 20 mL of THF and 1.0 g (6 mmol) of benzyl bromide had been placed and cooled to 0°C. The mixture was stirred for one hour at 0°C and for an additional hour at 40C. Next the THF was evaporated and the crude was extracted between H₂O and CH₂Cl₂. 0.80 g (64% yield) of 3-Benzyl-2,4-pentanedione, **3**, was isolated from the organic layer.

Comparison of the Relative Efficiencies of CoCl₂(PPh₃)₂ and CoCl(PPh₃)₃ as Catalysts in the Reaction of Pentane-2,4-dione with 1-Bromo-1-phenylethane. 1-Bromo-1-phenylethane (0.270 g, 1.46 mmol), pentane-2,4-dione (0.146 g, 1.46 mmol), potassium carbonate (4.84 g) and 2 mL of chloroform were introduced in three 25 mL sealed flasks. 95 mg (0.1 eq) of CoCl₂(PPh₃)₂ was added to one reactor, and 128 mg (0.1 eq) of CoCl(PPh₃)₃ was added to another (under inert atmosphere), leaving the third as a blank. The reaction mixtures were heated for 5 h at 80°C. The crude reaction mixture were washed with water and the organic layers were directly studied by gas chromatography. The relative chromatographic areas of the peaks corresponding to the starting 1-bromo-1-phenylethane and the final alkylation product, 3-(1-phenylethyl)pentane-2,4-dione, **1**, were compared. The results were: flask 1 (CoCl₂(PPh₃)₂ as catalyst), SM (starting material) / FP (final product) = 2/98; flask 2 (CoCl(PPh₃)₃ as catalyst), SM/FP = 1/99; flask 3 (blank reaction), SM/FP = 88/12.

Reaction of (acac)₂Co with a Mixture (1:1) of 1-Phenylethanol and 1-Bromo-1-phenylethane. 1-Phenylethanol (0.178 g, 1.46mmol) , 1-bromo-1-phenylethane (0.270 g, 1.46 mmol), (acac)₂Co (0.375 g, 1.46 mmol), and 2 mL of chloroform were introduced in a 25 mL round bottom flask equipped with a reflux condenser, . The reaction mixture was heated at 120°C for five minutes, and the solvent was evaporated by removing the condenser. The mixture was maintained at this temperature in the open air for 6 h. The crude rection mixture was dissolved in chloroform and washed several times with a 1M HCl and with water. The organic layer was evaporated and the residue was purificated as previously indicated, yielding 0.455 g of 3-(1-phenylethyl)pentane-2,4-dione, **1** (75% yield) described in a previous paragraph.

Reaction of (acac)₂Co with a Mixture (1:1) of 1-Phenylethyl Acetate and 1-Bromo-1-phenylethane. 1-Phenylethyl acetate (0.239 g, 1.46 mmol) , 1-bromo-1-phenylethane (0.270 g,1.46 mmol), (acac)₂Co (0.375 g, 1.46 mmol) and 0.5 mL of chloroform were introduced into a 25 mL sealed flask, . The reaction

mixture was heated overnight at 80°C. The crude was worked up as usual yielding 0.452 g of 3-(1-phenylethyl)pentane-2,4-dione, 1 (76% yield).

Kinetic Studies

General Procedure for the Studies Reported in Tables 1-9. 1.46 mmol of the alkyl halide, 0.731 mmol of (acac)$_2$Co, and the appropiate amount of chloroform to achieve the indicated concentration were introduced into several 25 mL sealed flasks, . The mixtures were heated at the indicated temperatures for the time given. In the experiments of table 7, the appropriate amount of galvinoxyl was also introduced. All the samples were worked up identically. The crude reaction mixture was washed with 1M HCl and with water. The organic layer was dried, the solvent evaporated, and the residue weighted. To minimize errors, the yields reported in the tables were obtained directly from the ^{1}H NMR spectra of the residues, except in the experiments of table 7 (galvinoxyl), where the spectrum was not clear enough. In this case, the reaction was quantified by gas chromatography, using phenanthrene as internal standard. Each value shown in Tables 1-9 is the result of averaging the yields obtained from two different runs . A limit 10% (15% in the low conversion data points) deviation between values from different runs was admited for a particular value to be considered.

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